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THE TimIQ SYNCHRONIZATION FOR SUB-PICOSECOND DELAY ADJUSTMENT

J-P. Ricaud†, N. Hubert, M. Labat, C. Laulhé[1], Synchrotron Soleil, St Aubin, France
H. Enquist, MAX IV Laboratory, Lund, Sweden
[1]also at Université Paris-Saclay, Saint-Aubin, France

Abstract

Synchrotron facilities provide short, regular and high frequency flashes of light. These pulses are used by the scientific community for time resolved experiments. To improve the time resolution, demands for always shorter X-ray pulses are growing. To achieve this goal, Synchrotron SOLEIL and MAX IV laboratory have developed special operating modes such as low-alpha and femtoslicing, as well as a single pass linear accelerator. For the most demanding experiments, the synchronization between short light pulses and pump-probe devices requires sub-picosecond delay adjustment. The TimIQ system has been developed for that purpose. It is a joint development between Synchrotron Soleil and MAX IV Laboratory. It is aimed to be used on three beamlines at Soleil and one at MAX IV. Based on IQ modulation technics, it allows shifting a radio frequency clock by steps of #100 fs. This paper is a description of this system and of its performances.

INTRODUCTION

Synchrotron facilities provide high frequency, high intensity and short pulses of light which are used by beamlines for pump-probe experiments. In such an experimental scheme, a sample is excited with an optical laser pulse, and the high frequency synchrotron light pulses are used to study the sample evolution over time [1] [2]. To study always faster phenomena, shorter x-ray pulses are required. SOLEIL provides low-alpha [3] and femtoslicing modes [4] for this purpose. At MAX IV the linac is built both for injecting the two storage rings as well as to provide short electron pulses for the Short Pulse Facility (SPF) [5]. At the SPF the electron pulses are sent through an undulator to provide 100 femtosecond (fs) x-ray pulses to the FemtoMAX beamline [6].

The synchronization of such experimental setups is getting more and more challenging. Delays and time offsets between the acquisition devices, the laser and the electron beam inside the storage ring (SOLEIL) or inside the accelerator tunnel (MAX IV) must be tuned very accurately, in range of few tenths of femtoseconds . For this purpose, SOLEIL and MAX IV have developed the TimIQ system. Based on IQ modulation technics, it allows delaying the laser's oscillator clock with sub-picosecond resolution.

IQ MODULATION

A sine wave signal is represented as a circle in the Cartesian coordinates with an in-phase (I) and a quadrature (Q) component. Changing one of those component changes the phase (ϕ) and the amplitude (A) of the signal (see Fig. 1).

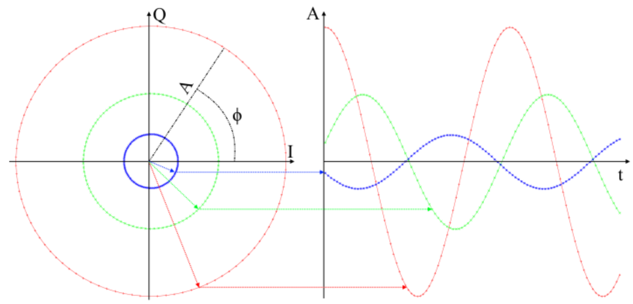

Figure 1: IQ modulation of a sine wave.

An IQ modulator device, also called a vector modulator, allows to adjust the phase and the amplitude of a radio frequency signal by modifying its I and Q components. Not only does it allow achieving very fine delay adjustment, but it also allows drifting infinitely the signal without any discontinuity: I and Q have the same value after a 360° phase shift. This is a major advantage over phase shifters and delay lines which have a limited phase shift range.

Many integrated circuit manufacturers provide IQ modulator chips making the design of this kind of solution for delay adjustment relatively straightforward. Fig. 2 illustrates how these chips work.

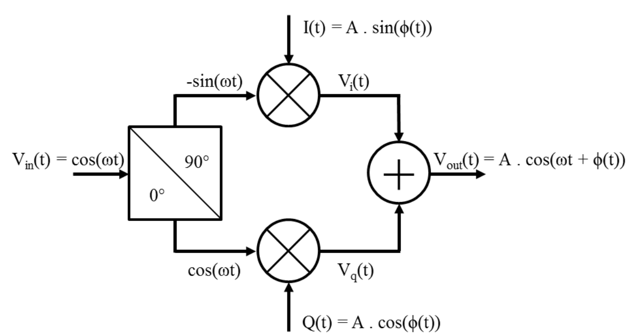

Figure 2: IQ modulator device schematic.

The input signal $V_{in}(t)$ is split in two branches. One of them is shifted by 90°. After multiplication by Q(t) and I(t), they are summed together to get the shifted output signal.

$$V_{in}(t) = \cos(\omega t)$$
$$V_q(t) = Q(t) \,.\, \cos(\omega t) = A \,.\, \cos(\phi(t)) \,.\, \cos(\omega t)$$
$$V_i(t) = I(t) \,.\, \cos(\omega t + \pi/2) = - A \,.\, \sin(\phi(t)) \,.\, \sin(\omega t)$$
$$V_{out}(t) = A \,.\, \cos(\phi(t)) \,.\, \cos(\omega t) - A \,.\, \sin(\phi(t)) \,.\, \sin(\omega t)$$

† jean-paul.ricaud@synchrotron-soleil.fr

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$$V_{out}(t) = A \cdot \cos(\omega t + \phi(t))$$

Usually when an IQ modulator is used as a phase shifter, the amplitude A of the output signal is kept constant to avoid any malfunctioning of electronic devices connected to it.

TIMIQ SYSTEM HARDWARE

In pump-probe experiments involving X-rays produced by electron accelerators, the laser's oscillator is driven by the radio frequency clock (RF) of the synchrotron. The RF also drives the radio frequency cavities of the storage ring making electrons bunch flying inside the storage ring synchronous to this clock. To adjust the delay offset between the laser and the electron bunch, the laser's oscillator clock needs to be phase shifted.

Soleil RF frequency is 352.196 MHz, whereas MAX IV RF frequency is 3 GHz. To make the system usable by both institutes, a PLL up-converts SOLEIL's RF clock to 2.8 GHz (see Fig. 3).

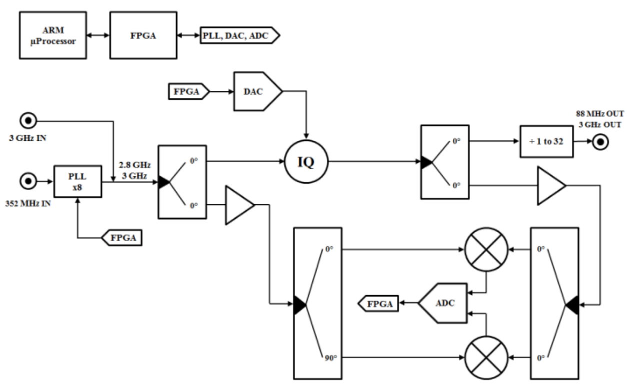

Figure 3: TimIQ architecture.

This signal is phase shifted by an IQ modulator which is controlled through an 18 bits Digital to Analog Convertor (DAC). The resulting signal is delivered to the laser oscillator either directly at 3 GHz for MAX IV or at 88 MHz after dividing the frequency by 32 for SOLEIL.

A readback on the actual phase shift is important for diagnostics and operation, especially when dealing with sub-picosecond delays. Two frequency mixers are used to measure the phase shift between the output and input signals. Due to high frequency signals, analog mixers are used instead of digital ones inside the FPGA. To improve the sensitivity of the measurement, the input of one of the mixer is shifted by 90°. After filtering, they provide two voltages, $V_{0°}$ and $V_{90°}$, which allows retrieving the phase shift:

$$V_{0°}(t) = B \cdot \cos(\phi(t))$$
$$V_{90°}(t) = C \cdot \cos(\phi(t) + \pi/2)$$

By toggling the measurement from one mixer to the other, it is possible to read the phase shift only on the linear part of the cosine function where the measurement is more accurate (see Fig. 4).

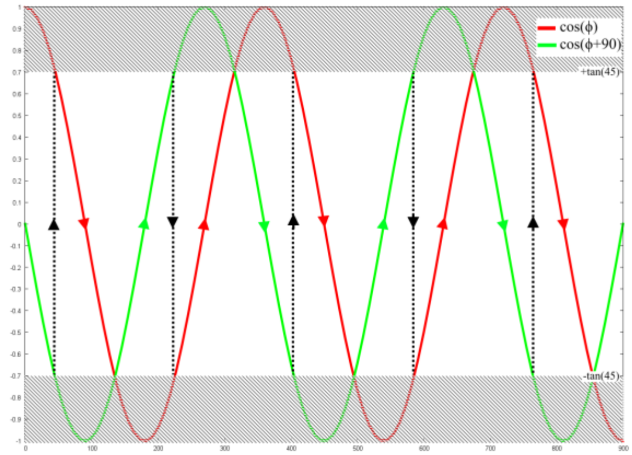

Figure 4: Mixers readout signal.

The mixers voltages are sampled with an 18 bits Analog to Digital Convertor (ADC). All components are managed with a FPGA. It transmits the data to an ARM microprocessor running a Linux operating system with an Apache web server [7]. The system can be controlled through Tango devices, python scripts or even with a simple web browser.

FIRST RESULTS

Phase Noise Jitter

The phase noise jitter has been measured by connecting directly the TimIQ system to a signal noise analyzer [8]. Fig. 5 describes the setup.

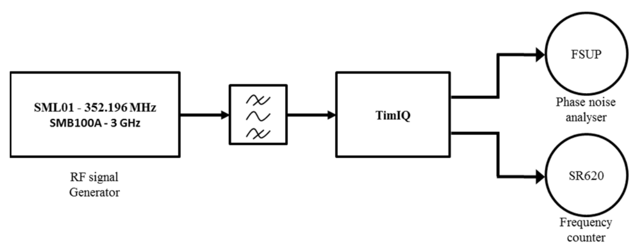

Figure 5: Phase noise jitter measurement setup.

Fig. 6 shows the resulting phase noise trace when the system is configured for SOLEIL usage (input 352.196 MHz; output 88.05 MHz). The spikes between 10 Hz and 2 kHz are due to the input RF clock. The PLL + VCO main contribution to the phase noise (2 kHz – 10 MHz) remains under -130 dBc/Hz with a peak at 80 kHz offset corresponding to the PLL loop bandwidth.

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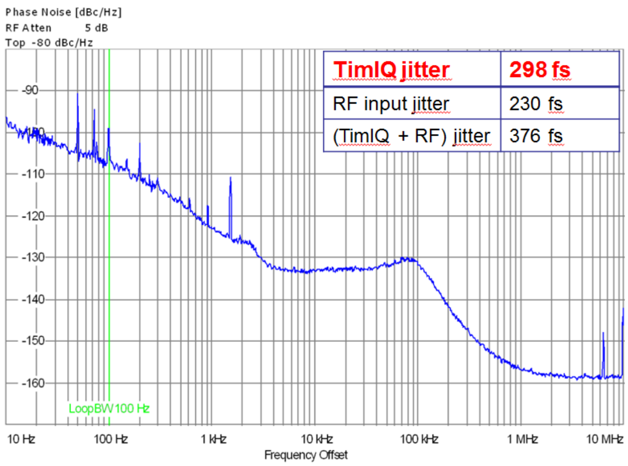

Figure 6: Phase noise jitter. SOLEIL configuration.

The phase noise jitters are summarized in Table 1 for SOLEIL and for MAX IV configurations.

Table 1: Phase Noise Jitter [10 Hz ; 10 MHz]

	SOLEIL @ 88 MHz	MAX IV @ 3 GHz
Jitter	298 fs RMS	177 fs RMS

IQ Modulator and Mixers Resolution

The phase shift between the input and the output of the TimIQ system is measured by two inboard mixers as explained above. When the output is delayed by steps of 40 fs, the readout from the mixer in its linear region where the resolution is the most accurate, is shown in Fig. 7. This measure cumulates the errors due to the IQ modulator and the errors due to the mixer itself.

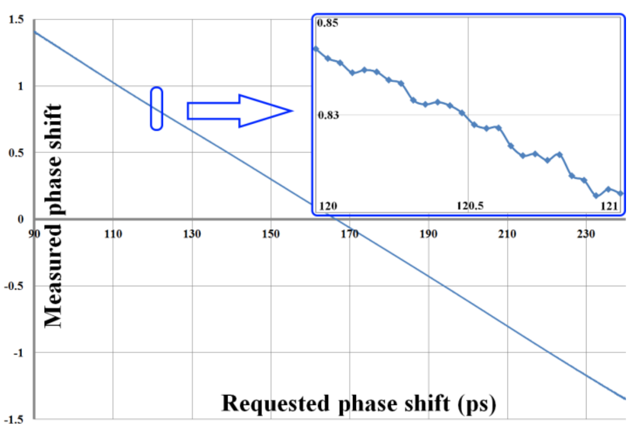

Figure 7: TimIQ resolution.

The resulting readout trace shows that the system reacts to 40 fs step requests.

Accuracy and Precision

The skew between the input and the output signals is measured with a 20 GHz, 80 GS/s oscilloscope [9]. This is done several times to measure the accuracy of the device (deviation of the actual signal with respect to its expected value) and its precision (repeatability over several periods and over several measurements). The difference between the measured and the requested phase shift is plotted on Fig. 8.

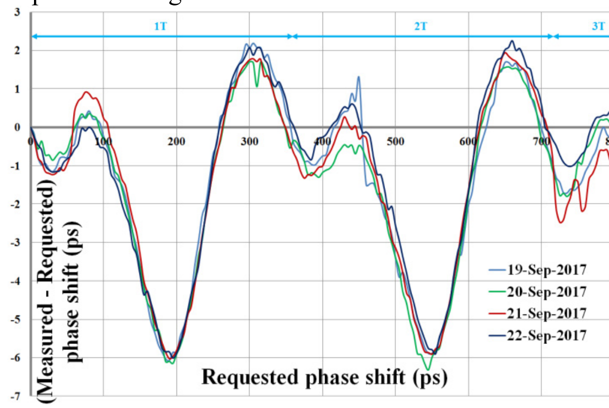

Figure 8: (measured - requested) phase shift.

The period of the signal is T = 1 / (8 * 352.196e6) = 355 ps. Fig. 8 shows a little more than 2 periods. The peak to peak difference between the measured and the requested phase shift is about 8.2 ps. The shape of the traces, with a peak deviation of -6 ps at 190 ps offset, is due to the IQ modulator chip. The oscilloscope itself has a typical hardware trigger jitter of 2 ps rms according to its datasheet.

The good repeatability of the traces allows to correct the error and to achieve a better accuracy by adjusting the I and the Q setting points according to Fig. 8 measurements. In the past, such error correction has allowed us to improve by almost a factor of 10 a former IQ modulator's accuracy.

CONCLUSION

Compared to the previous system used at SOLEIL, the TimIQ brings several improvements. The phase noise jitter has been reduced from 950 fs to 298 fs. The accuracy has dropped from 48 ps to 8.2 ps. Measurements with the inboard mixers show that the system is capable to add delays down to 40 fs.

With an appropriate control software it is possible to greatly improve the accuracy and to compensate the phase error. Adding to that the 40 fs resolution of the device, it should be possible to adjust delays down to #100 fs or even less. For this purpose, mixers have been included on the TimIQ, but their performance characterization and the feedback algorithm is still a job to carry out.

The next step will be to put in operation the TimIQ on CRISTAL beamline at SOLEIL and on FemtoMAX beamline at MAX IV and to confirm the performance of this system in real operation.

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[9] Teledyne Lecroy, SDA 820 Zi-B, 20 GHz, 80 GS/s.